HF Surface Wave Radar for Oceanography - A Review of Activities in Germany -

(Invited Paper)

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***Abstract*— The remote sensing group of the University of Hamburg is working in the field of HF radar since 1980. For the start three CODAR systems have been purchased from NOAA/ERL (developed by D. Barrick's NOAA group). Based on 16 years of experience a new system called WEllen RAdar (WERA) has been designed at the University of Hamburg in 1996. The new design aims to be as flexible as possible in order to allow easy adjustment to different requirements, i.e. working frequency, spatial resolution, and antenna configurations. The first part of this paper describes the technical solutions available to achieve resolution in range and azimuth. Modulation techniques for range resolution like Pulses and Frequency Modulation (FMCW) are compared, as well as Direction Finding and Beam Forming for azimuthal resolution. A short introduction to the algorithms is given. The second part discusses the hardware and software components which form a WERA and are now commercially available. The third part shows an example of a monitoring system bringing together HF radar remote sensed data and numerical models.**

I. Introduction

In 1980, one year after the Marine Remote Sensing (MARSEN) Experiment [3], the University of Hamburg Remote Sensing Group started working on HF radar. In close cooperation to the HF radar group at NOAA[1], at that time lead by D. Barrick [1], three Coastal Ocean Dynamics Application Radars (CODAR) systems have been purchased. The NOAA-CODAR is completely different from the actual SeaSonde which is now delivered from D. Barrick's company "CODAR Ocean Sensors". It uses a Continuous Wave (CW) pulsed modulation scheme for range resolution and 4 receive antennas arranged in a sqare for azimuthal resolution.

In 1981, the first experiment with the University of Hamburg CODAR took place on the island of Sylt, Germany [4]. Until 1983, several modifications have been done to improve the sensitivity. The working frequency has been increased from 25.4 MHz to 29.85 MHz in order to reduce the impact from radio interference due to ionospheric reflections and between 1983 and 1990, a shipborne version [7] of CODAR has been developed.

[1]National Oceanic and Atmospheric Administration, USA

In autumn 1983, the Canadian Memorial University of Newfoundland in St. John's organized an "International Workshop on the Remote Sensing of Oceanic Variables Using HF Groundwave Radar". On this workshop E. D. R. Shearman presented results of his PISCES HF radar system [13], which used "Frequency Modulated Interrupted Continuous Wave" (FMICW) modulation for range resolution and a large linear array of receiving antennas for azimuthal resolution. Due to the low working frequency around 9 MHz, the working range of this system was as large as 150 km for ocean wave measurements and even more for currents. This presentation provided the initial ideas for the University of Hamburg WEllen RAdar (WERA), however it needed another 12 years to bring together the complete design and the money to build a prototype WERA [8]. Meanwhile a commercial version of WERA is available.

II. Spatial resolution of an HF radar

As with every radar, spatial resolution is required to distinguish targets or, in case of a radar for oceanography, different patches of the sea surface. The following sections describe modulation techniques for range resolution of an HF radar as well as antenna designs and algorithms for azimuthal resolution. The most complete discussion of these topis can be found at [9] and [10].

A. Range resolution by CW pulses

The NOAA-CODAR uses coherent CW pulses for range resolution. The length of the pulse determines the spatial resolution in range, e.g. a pulse with a duration of $8\,\mu s$ corresponds to a 1.2 km wide circle around the radar. The radio bandwidth B required for this resolution is $B = 1/(8\,\mu s) = 125$ kHz. However, due to time multiplexing ranges and antennas (cf. figure 1) the effective sampling rate for a specific range cell and antenna is much less: 488.3 Hz in this case. Thus, aliasing can not be avoided by a matching analog low pass filter. As a consequence noise and interference signals are aliased back. Adding up these noise bands reduces the signal-to-noise ratio by 24 dB. This is one of the reasons why the NOAA-CODAR

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like all pulsed radar systems uses high power pulses, e.g. 5 kW with an average of 100 W.

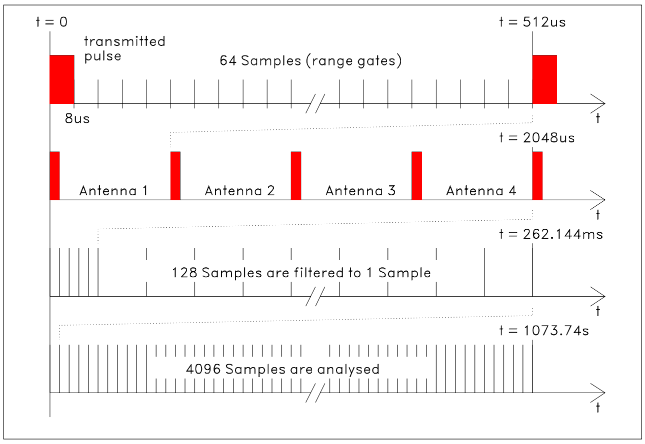


Fig. 1. The timing used within the NOAA-CODAR: 64 ranges and 4 antennas are multiplexed with time.

Advantages of the pulse technique are its simplicity and the fact, that an echo is always sampled into the correct range cell, even if it is scattered from a target producing a Doppler shift above Nyquist, e.g. a ship at high speed. In this case the echo is aliased to the wrong Doppler shift. Disadvantages are the high peak power needed and the bad compatibility with other radio services [13].

B. Range resolution by FMCW

Performing the range resolution in frequency domain, solves some of the problems described above. By using a continuously transmitted signal which is linearily increasing in frequency with time, an echo at a time delay Δt will appear at a constant frequency offset of Δf (cf. figure 2). The frequency of the chirp starts at f_0 and increases to $f_0 + B$ during the time T, B being the bandwidth of the chirp and c the speed of light. This process maps a target at the distance r to a frequency offset

$$\Delta f = \frac{B}{T}\frac{2r}{c} .$$

The received signal is mixed (multiplied) with the actual transmitted signal providing the frequency offset. This signal is transformed by a Fast Fourier Transform (FFT) to resolve ranges. The spectral lines of this range resolving FFT are quantized to

$$\Delta f_{quant} = \frac{1}{T} = \frac{B}{T}\frac{2r_{quant}}{c} .$$

In terms of range cell depth, this frequency quantization corresponds to

$$r_{quant} = \frac{c}{2B} .$$

A range resolution $r_{quant} = 1.2$ km again requires a bandwidth of $B = 125$ kHz. To avoid range smearing, a windowing function has to be applied prior to each FFT [10]. By tracking the phase of consecutive chirps, the Dopper spectra within the ranges can be resolved.

The advantages of FMCW modulation are the low continuously transmitted power (30 W in the case of WERA), and a better compatibility with other radio services as compared to CW pulses. Disadvantages are the required high dynamic range of the receiver, which has to handle the strong signal from the direct path (transmit antenna to receive antenna) and the weak signals from far ranges simultaneously as well as a more complex way of signal processing. Also, an echo generating a Doppler shift above Nyquist frequency will be shifted to a wrong range cell. Modern chips and software techniques meanwhile solved most of these difficulties.

C. Azimuthal resolution by Direction Finding

Two different techniques to resolve the incident angle of a sea echo are Direction Finding and Beam Forming. Direction Finding makes use of the amplitude and/or phase characteristics of a signal at multiple receive antennas. Figure 3 shows the NOAA-CODAR approach using 4 antennas in a square

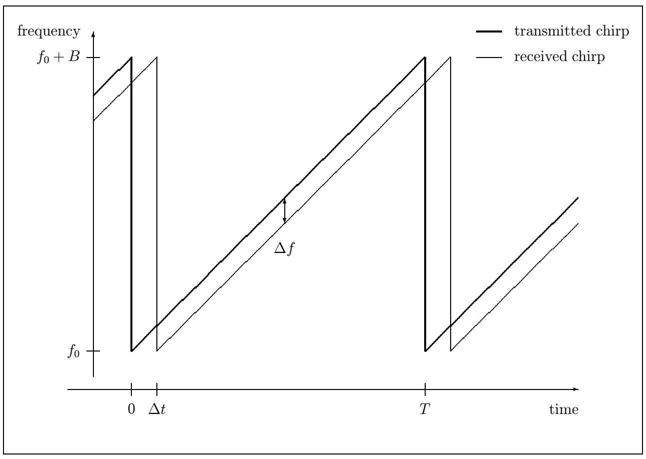


Fig. 2. A linear frequency chirp starting at f_0 with the bandwidth B and a duration T. After reaching the end frequency $f_0 + B$, the chirp's phase contiguously starts again at f_0.

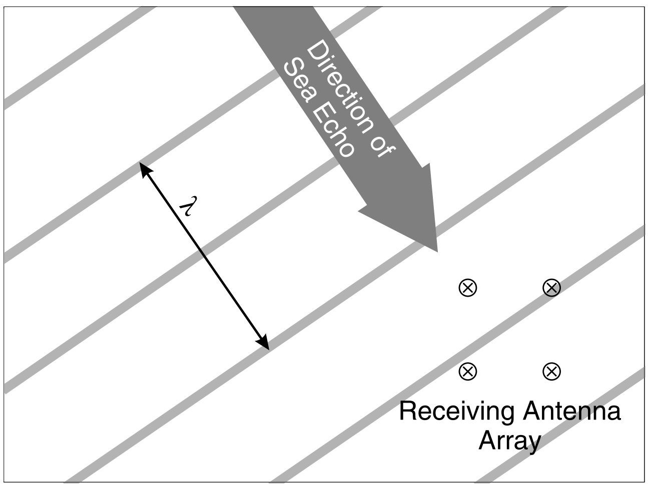


Fig. 3. A sea echo arriving from the upper left which causes a phase difference between the antennas.

with $\lambda/2$ or slightly less diagonal distance. An echo directed from the upper left in the figure arrives at the 4 antennas with a short time delay, which can be measured as a phase difference. Signals coming from different directions are identified by a changing set of phase differences.

If phase information is used, the incidence angle of a signal can be resolved by a least-squares-fit of the measured phase differences to the calibrated phases:

$$\varepsilon(\Theta) = \sum_{i=1}^{4} (\varphi_i^\star - \varphi_i(\Theta))^2$$

$$\varepsilon(\Theta) \Longrightarrow Minimum$$

with $\varphi_i^\star$ being the measured set of phase difference, $\varphi_i(\Theta)$ being the calibrated values, and Θ being the incidence angle. The sum $\varepsilon(\Theta)$ goes to a minimum at the most propable incidence angle.

In absense of noise, the measured set of phase differences and the calibrated values are identical, giving the exact solution. With increasing noise, the fitted incidence angle gets more and more uncertain, i.e. the azimuthal resolution is a function of signal-to-noise. If the antenna patterns are distorted, i.e. there are deviations from the theorectical functions of phase differences, additional systematic errors can be introduced, even if the distorted patterns are known and have been taken into account.

An algorithm based on amplitudes requires a unique relationship between azimuthal angle and amplitude. For example, two loop antennas installed perpenticular to each other like with D. Barrick's SeaSonde [11] could be used. Recently, an algorithm based on MUltible SIgnal Characterization (MUSIC) [12] has been implementedby D. Barrick for the SeaSonde. All these crossed-loop algorithms are patented by "CODAR Ocean Sensors", but their performance has not been evaluated by the authors of this paper.

Non of the published direction finding techniques is capable of resolving the second-order sea echo spectrum, which is located around the two first order peaks. Also, the algorithms run into trouble when, at a given Doppler shift, sea echos from multible directions superpose. If the number of superposed directions is limited and the signal-to-noise ratio is high, MUSIC can help to solve this case.

D. Azimuthal resolution by Beam Forming

If access to the complete backscatter Doppler spectrum from a specific patch of the sea surface is required, e.g. to get the second order returns for measuring ocean wave directional spectra, a linear array and beam forming should be used. As always, nothing is for free, and the price to pay in this case is the increased amount of space needed to install the linear array. A 16 antenna array operated at 30 MHz with $\lambda/2$ spacing between the antennas requires a 75 m long patch along the shore.

By shifting the phase between antenna signals and adding them up, a beam can be steered to about ± 60 degrees to a line perpendicular to the array. Figure 4 shows the antenna pattern of a 16 antenna array. To reduce side lobes in the antenna pattern, a windowing function has to be multiplied to the amplitudes of the antennas before the signals are shifted in phase and added up to steer the beam.

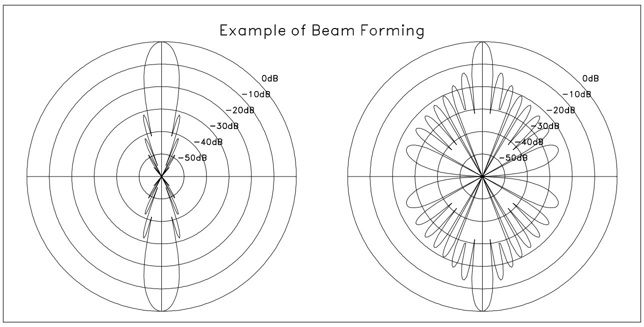


Fig. 4. The antenna pattern of a linear array with 16 antennas at $\lambda/2$ spacing (right side). A windowing function has to be applied to reduce side lobes (left side).

A linear array has a large aperture and is quite insensitive against distortions due to the environment. In many cases the beam forming gives more reliable results than direction finding, and for access to the full backscatter Doppler spectrum it is mandatory in any case.

III. THE HF RADAR WERA

The University of Hamburg WERA has been initially developed in 1996 within the EU funded Surface Current And Wave Variability Experiment (SCAWVEX) project. One main difference to the NOAA-CODAR is the use of FMCW modulation for range resolution instead of pulses. Azimuthal resolution can be achieved by software (beam forming or direction finding), depending on the actual receive antenna configuration and software modules applied. WERA consists of several hardware components which can be put together in a modular way, i.e. it is possible to start with a small 4-antenna system and direction finding and upgrade to a 16-antenna system later on.

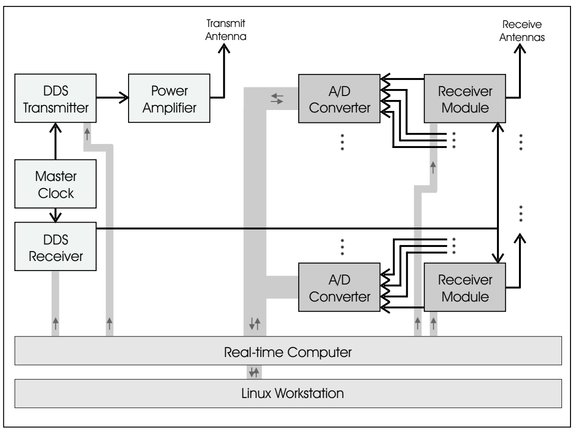


Fig. 5. The block diagram of the WERA system.

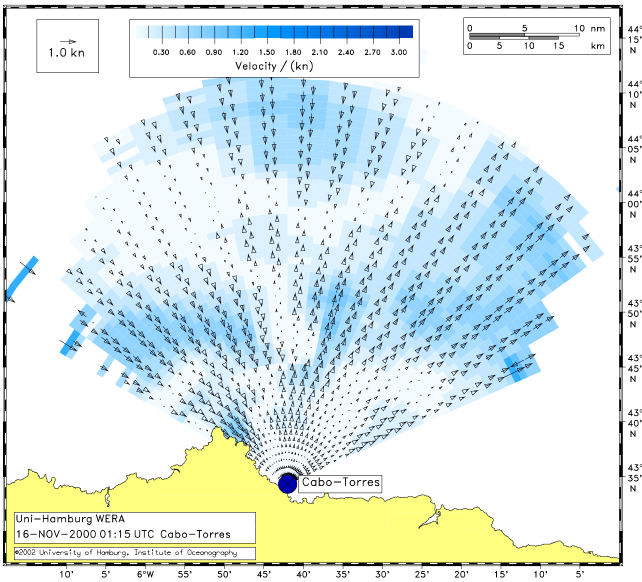


Fig. 6. Radial components of a surface current field measured by WERA at 27.65 MHz.

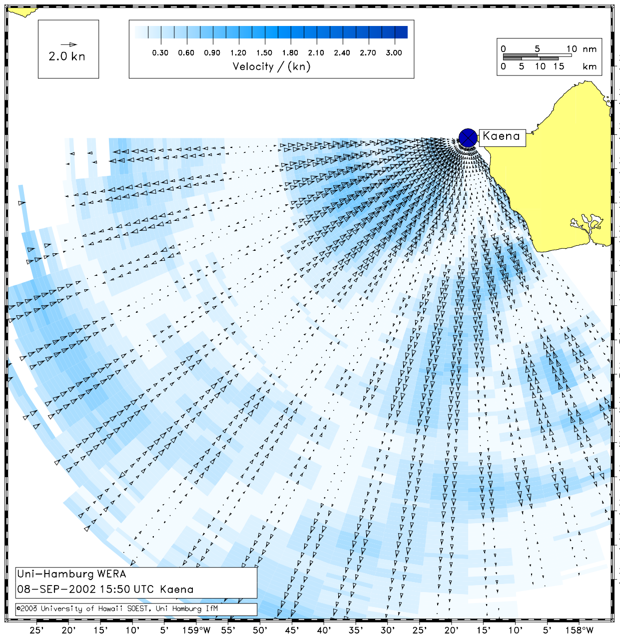


Fig. 7. Radial components of a surface current field measured by WERA at 16.05 MHz.

A. WERA hardware components

The heart of the system is a low-noise 180 MHz crystal oscillator, which is used as a master clock for all frequency generation and sampling (cf. figure 5). This concept makes the whole system strictly synchronized and coherent. There are two independent, synchronized DDS chirp generators, which produce the transmit and receive chirps at the desired working frequency. In this way constant frequency offsets between transmit and receive chirps can be programmed. The transmit signal is amplified to an output power of 30 W.

There is one receiver module for each receive antenna. Each receiver includes an HF band pass filter, an I/Q demodulator, and lowpass filters to avoid aliasing. High dynamic range components have been used to simultaneously handle the strong signal from the direct path and the weak sea echos from far ranges. Amplitude variations and phase shifts between the antennas and receivers are measured and compensated by software.

Each A/D converter module handles the demodulated I/Q signals of four receivers. The software automatically scans and configures the correct number of installed receiver channels in steps of four. Besides programming the DDSes and controlling the A/D converters, WERA's real-time computer on-line performs the range resolving FFTs. The real-time computer is connected to a Linux workstation which controls the measurement cycles and stores and processes the measured data.

B. WERA software components

Basically there are three software packages to run WERA: The real-time software on the WERA itself, the WERA control and calibration software which runs on the Linux workstation, and the data processing software which runs on the Linux workstation, too.

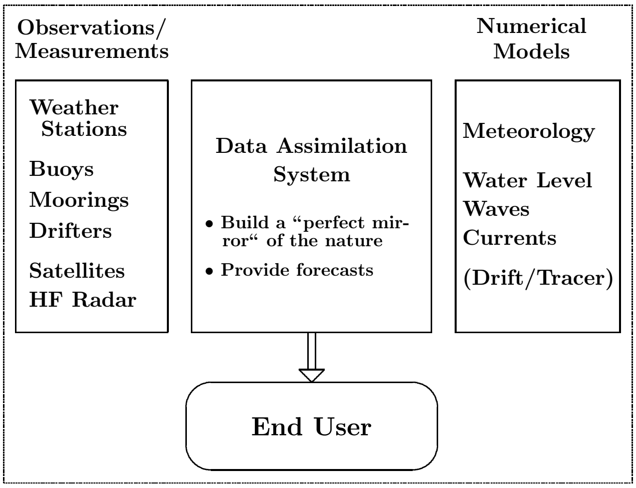
There is a human interface "WeraDesk" to control and set-up WERA measurement cycles. This software provides a web-based interface which can be accessed remotely through the Internet depending on the configuration options selected for the Apache web server which runs on the Linux workstation.

Besides controlling the measurement cycle- and repetition times, the following radar characteriscicts can be set: The range cell depth can be set to 3.0 km. . .0.3 km, the number of range cells to 32. . .256, the samples per data run to 64. . .4096, and the sample rate to 0.173333 s (good to resolve Bragg lines at 68 MHz). . .0.520000 s (Bragg lines at 7.5 MHz). The working frequency can be set to anywhere between 7.5 MHz and 68 MHz, but the correct filters have to be installed inside the receiver modules and the transmit power amplifier. Also the antennas must be designed for the configured working frequency.

The data processing software performs azimuthal resolution (there are algorithms for direction finding and beam forming as described before) and calculates current maps or ocean wave information. Other software modules can visualize the measurement or calibration results. If there are data links to the WERA sites available, a real-time monitoring system can be set up.

C. WERA measurement examples

Up to now, WERA has been operated at 29.85 MHz, 27.65 MHz, and 16.05 MHz. In the very near future, 12.477 MHz will be used during an experiment. As expected, the attenuation of the backscattered signals increases with



Vessel Traffic Services:	Waves, Currents → **EuroROSE**
Port Authorities:	Water Level, Storm Surge, ETA
Captains and Pilots:	Waves, Currents, Route Optimization
Search and Rescue:	Waves, Drift (shipwrecked person)
Environment Authorities:	Water Level, Storm Surge, Drift (oil)

Fig. 8. The main components of an Operational Forecasting System and some examples of users of such a system.

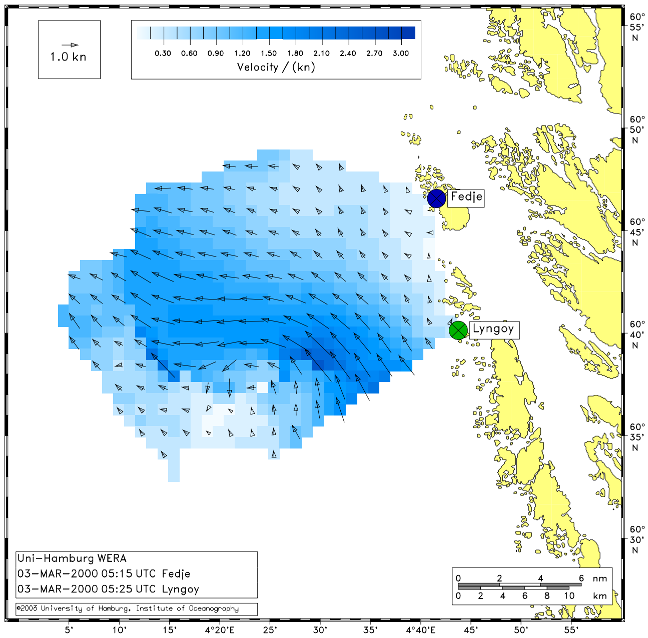


Fig. 9. EuroROSE Fedje experiment: The surface current field measured by HF radar at the 3rd March 2000 5:15 UTC. A strong meandering front can be seen west off the Lyngoy site.

frequency, giving a working range of up to 60 km (cf. figure 6) at 27 MHz and up to 150 km at 16 MHz (cf. figure 7). At 12.5 MHz we expect working ranges up to 200 km. The range resolution of WERA was possible to be set to values as low as 300 m at 27 MHz and 1.2 km at 16 MHz.

IV. An Ocean Monitoring System

In the frame of GOOS[2] and its European component EuroGOOS, operational forecasting of current and wave fields in coastal regions got more and more important in the last decades, both for coastal management and for security aspects. A good overview on EuroGOOS activities can be found at [5]. One of the key components in this context are high-resolution numerical models, which however require accurate forcing and handling of the boundary conditions. HF radar remote sensed current and wave fields can significantly increase the data quality of the model products through data assimilation. In some cases, when the oceanographic processes induce high local variability, such as mesoscale eddies and fronts, this approach might be the only way to provide reliable now- and forecasts.

The general structure of a monitoring system is given in figure 8. The aim is to provide accurate on-line access to the actual situation, where on-line means a delay of one hour at maximum, and to provide forecasts. This could be achieved by a synergy of observations and numerical models, i.e. by linking radar based measurements to fine-resolution models by data assimilation. The measured data are required to force the model close to nature, whereas the model is needed for interpolation and forecasts.

[2]Global Ocean Observing System

On the measurement side, there is e.g. the already established network of weather stations. This network is delivering data to the meteorological models, which provide the results to the weather services. The quatilty of these services especially regarding the 2 to 3 day forecasts has significantly increased during the last 10 years due to the synergy of observations and numerical models. One of the aims of GOOS is to extend the monitoring system from the atmosphere to the ocean by including the observations of buoys, moorings, drifters, and remote sensing techniques like satellites and ground-based HF radars to the numerical models of the ocean by data assimilation.

Figure 8 also lists some end users of such a monitoring service, e.g. Vessel Traffic Services (VTS), port authorities, captains and pilots on sailing ships, search and rescue operations, and environment authorities. An example of a monitoring system especially designed for VTS operations has been demonstrated within the European Radar Ocean Sensing (EuroROSE)[6] project, where the safe navigation of oil tankers between the Norwegian islands has been supported.

During the EuroROSE experiments, two WERA HF radars have been installed, north and south of the entry. The distance between the WERAs was about 13 km. Figure 9 shows a surface current map measured by WERA.

On the model side, a nested approach has been used. There was a three step model chain for currents: The outer model covers the North Atlantic and the Norwegian Sea with a resolution of about 20 km. This model delivers boundary conditions to an intermediate model (4 km resolution) of the coastal waters of southern Norway, which in turn provides boundary conditions to the high-resolution EuroROSE model

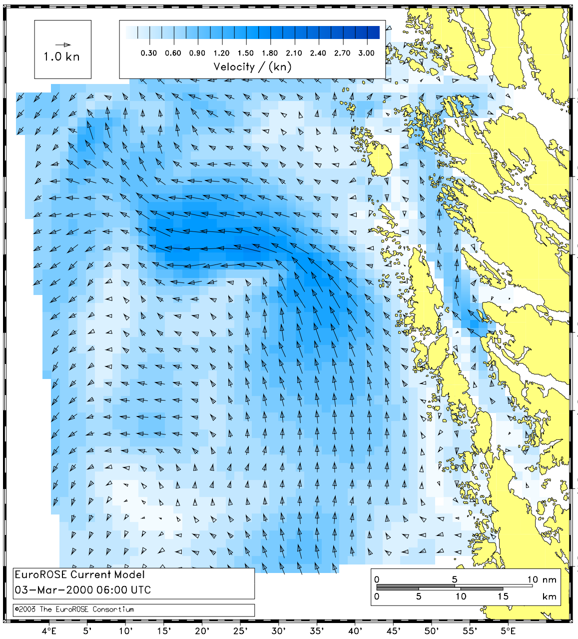


Fig. 10. EuroROSE Fedje experiment: The surface current field calculated by the model after data assimilation of the HF radar current field shown in figure 2.

of the target area (60 km ⋆ 60 km).

The numerical models have been operated by the Norwegian Meteorological Institute (met.no), the data assimilation technique has been developed by the Norwegian Nansen Environmental and Remote Sensing Center (NERSC). The model and data assimilation technique is described by Breivik and Sætra [2].

Figure 10 shows a current field delivered by the model/data assimilation system. The oceanographic front can still be seen, although it appears to be smoothed. The model results represent the top 10 m of the sea surface (this is affecting the navigating ships), while figure 9 shows the measured current velocity at the very top 0.5 m.

To get an estimate of the performance of the system, now- and forecasts have been compared to actual measurements. As expected, the nowcast and the measurement show an rms error as low as 10 cm/s for a position in the center of the measurement area. When comparing the 2- to 6-hour forecasts with the measurements taken at that time, the rms error increases to 20 cm/s. Breivik and Sætra, 2001, present scatter plots and correlations for the different forecast steps. The correlation factor is 0.89 for the nowcast, 0.85 for the 2-hour forecast, 0.77 for the 4-hour forecast, 0.63 for the 6-hour forecast, and 0.27 for a free running model without data assimilation. The last number shows the importance of measured data to be included into the monitoring system.

V. Conclusions

The University of Hamburg HF radar WERA has been developed in 1996 and is based on 20 years of experience with development and application of HF radars. It offeres a modular design which can easily be adopted to the requirements of different applications. When operated at 16 MHz, a working range of up to 150 km for current measurements can be obtained. HF radars play an increasingly important role within monitoring systems of the ocean to provide accurate now- and forecasts to customers like Vessel Traffic services.

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